THE ORIGIN AND EVOLUTION OF LIFE UPON THE EARTH[1]

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LECTURE I. PART III

Biochemical Evolution of Bacteria—Evolution of Protoplasm and of Chromatin—The Fundamental Biologic Law—Chlorophyll and the Energy of Sunlight -Algæ.

PRIMARY STAGES OF BIOCHEMICAL EVOLUTION IN BACTERIA

A BACTERIA-LESS earth and a bacteria-less ocean would soon be uninhabitable either for plants or animals; conversely, it is probable that bacteria-like organisms prepared both the earth and the ocean for the further evolution of plants and animals, and that life passed through a very long bacterial stage.

Owing to their minute size or actual invisibility bacteria are classified less by their shape than by their chemical actions, reactions, and interactions, the analysis of which is one of the triumphs of modern research. In the origin of life they lie half way between the hypothetical chemical pre-cellular stages (pp. 179–189) and the chemistry and definite cell structure of the lowliest plants or algae. The size of bacteria is in inverse ratio to their importance in the primordial and present history of the earth. The largest known are slightly above 1/20 of a millimeter in length and 1/200 of a millimeter in width.[2] The smaller forms range from 1/2000 of a millimeter to organisms on the very limit of microscopic vision, 1/5000 of a millimeter in size, and to the bacteria beyond the limits of microscopic vision, the existence of which is in-

[1] Fourth course of lectures on the William Ellery Hale Foundation, National Academy of Sciences, delivered at the meeting of the academy at Washington, on April 17 and 19, 1916. The author desires to express his special acknowledgments to Professor E. B. Wilson, of Columbia University, Dr. I. J. Kligler, of the American Museum of Natural History, Professor T. H. Goodspeed, of the University of California, and Dr. M. A. Howe, of the New York Botanical Garden, for notes and suggestions used in the preparation of this section.

[2] The influenza bacillus, 5/10 × 2/10 of a micron (1/1000 mm.) in size, and the germ of infantile paralysis, measuring 2/10 of a micron, are on the limit of microscopic vision. Beyond these are the ultra-microscopic bacteria, some of which can pass through a porcelain filter. See Jordan, Edwin O., 1908, pp. 52, 53.

ferred in certain diseases. The chemical constitution of these microscopic and ultra-microscopic forms is doubtless highly complex.

In their power of finding energy or food in a lifeless world the bacteria known as *prototrophic* or "primitive feeders" are not only the simplest known organisms, but it is probable that they represent the survival of a primordial stage of life chemistry. These bacteria derive both their energy and their nutrition directly from inorganic chemical compounds: such types were thus capable of living and flourishing on the lifeless earth even before the advent of continuous sunshine and long before the first chlorophyllic stage (Algæ) of the evolution of plant life. Among such bacteria possibly surviving from Archeozoic time is one of these "primitive feeders," namely, the *Nitroso monas* of Europe.[3] For combustion it takes in oxygen directly through the intermediate action of iron, phosphorus, or manganese, each of the single cells being a powerful little chemical laboratory which contains oxidizing catalyzers, the activity of which is accelerated by the presence of iron and of manganese. Still in the primordial stage *Nitroso monas* lives on ammonium sulphate, taking its energy (food) from the nitrogen of ammonium and forming nitrites. Living with it is the symbiotic bacterium *Nitrobacter,* which takes its energy (food) from the nitrites formed by *Nitroso monas,* oxidizing them into nitrates. Thus these two species illustrate in its simplest form our law of the *interaction of an organism* (*Nitrobacter*) *with its life environment* (*Nitroso monas*).[4]

The discovery of the chemical life of these bacteria marks an advance toward the solution of the problem of the origin of life as important as that attending the long prior discovery of chlorophyll. The prototrophic forms above noted are classed among the *nitrifying bacteria:* they take up the nitrogen of ammonia compounds and oxidize them first into nitrites and then into nitrates. Heraeus and Hüppe (1887) were the first to observe these forms in action in the soils and to prove that pre-chlorophyllic organisms were capable of development, with ammonium and carbon dioxide as their only sources of energy. Eight chemical "life elements" are involved in this process, namely, potassium, phosphorus, magnesium, sulphur, calcium, chlorine, nitrogen, and carbon. This discovery was confirmed by Winogradsky (1890, 1895), who showed that two symbiotic groups existed; one the *nitrite* formers, *Nitroso monas,* and the other the *nitrate* formers, *Nitrobacter.* These bacteria are not only independent of life compounds, but even small traces of organic carbon and nitrogen compounds are injurious to them. Later Nathanson (1902) and Beyjerinck (1904) showed that certain sulphur bacteria possess similar powers of converting ferrous to ferric oxide, and H_2S to SO_2. These organisms are widespread:

[3] Fischer, Alfred, 1900, pp. 51, 104.

[4] Jordan, Edwin O., 1908, pp. 492–497.

Nitroso monas is found in Europe, Asia, and Africa, while *Nitrobacter* appears to be almost universally distributed.

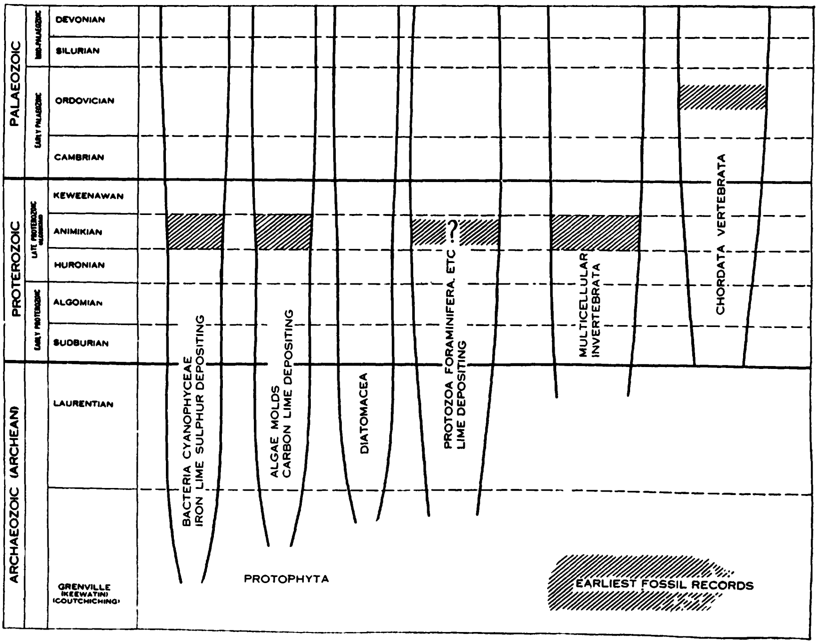

FIG. 1. PRE-CAMBRIAN PHYLÆ OF PLANT AND ANIMAL LIFE.

Such bacterial organisms may have flourished on the lifeless earth and prepared both the earth and the waters for the higher forms of plant life. The relation of the *nitrifying bacteria* to the decomposition of rocks is well summarized by Clarke in the following passage:[5]

Even forms of life so low as the bacteria seem to exert a definite influence in the decomposition of rocks. A. Müntz has found the decayed rocks of Alpine summits, where no other life exists, swarming with the nitrifying ferment. The limestones and micaceous schists of the Pic du Midi, in the Pyrenees, and the decayed calcareous schists of the Faulhorn, in the Bernese Oberland, offer good examples of this kind. The organisms draw their nourishment from the nitrogen compounds brought down in snow and rain; they convert the ammonia into nitric acid, and that, in turn, corrodes the calcareous portions of the rocks. A. Stützer and R. Hartleb have observed a similar decomposition of cement by nitrifying bacteria. The effects thus produced at any one point may be small, but in the aggregate they may become appreciable. J. C. Branner, however, has cast doubts upon the validity of Müntz's argument, and further investigation of the subject seems to be necessary.

It is noteworthy that it is the *nitrogen derived from waters and soils,* rather than from the atmosphere, which plays the chief part in the life of these organisms; in a sense they represent a pre-carbon stage

[5] Clarke, F. W., 1916, p. 485.

of chemical evolution, also adaptation to an earth and water environment rather than to an atmospheric one.

In our study of the chemistry of the lifeless earth it has been shown how the life elements essential for the energy and nutrition of the nitrifying bacteria, namely, sodium, potassium, calcium and magnesium, with potassium nitrite and ammonium salts as a source of nitrogen, were probably accumulated in the waters, pools and soils. These bacteria were at once the soil-forming and the soil-nourishing agents of the primal earth; they throve in the presence of energy-liberating compounds of extremely primitive character. It is important to note that water and air are essential to vigorous ammonium reactions, whether at or near the surface. In arid regions at the present time the ammonifying bacteria do not exist on the dry surface rocks but act vigorously in the soils, not only at the surface, but also in the lower layers at depths of from six to ten feet where moisture is constant and the porous soil well aerated,[6] thus giving rise to a nitrogen-nourished substratum which explains the deep rooting of desert-dwelling plants.

A second point of great significance is that these nitrifying organisms are *heat-loving* and *light-avoiding;* they are dependent on the heat of the earth or of the sun, for, like all other bacteria, they carry on their activities best in the absence of sunshine, direct sunlight being generally fatal. The sterilizing effect of sunlight is due partly to the coagulation of the bacterial colloids by the rays of ultra-violet light. The sensitiveness of bacteria to sunlight cannot, however, be used as an argument against their geologic antiquity; on the contrary, their undifferentiated structure and their ability to live on inorganic foodstuffs *even without the aid of sunshine* seem to favor the idea that they represent a very primitive form of life.[7]

The great antiquity even of higher forms of bacteria feeding on atmospheric nitrogen is proved by the discovery, announced by Walcott[8] in 1915, of a species of pre-Paleozoic fossil bacteria attributed to "*Micrococcus*" but probably related rather to the existing *Nitroso coccus* which derives its nitrogen from ammonium salts. The *Nitroso coccus* is the form found in this country corresponding to the *Nitroso monas* of Europe. Its mode of life is identical with that of the *Nitroso monas*. These fossil bacteria were found in a section of a chlorophyll-bearing algal plant from the Newland limestone of the Algonkian of Montana, the age of which is estimated to be about thirty-three million years. They point to a very long antecedent stage of bacterial evolution.

6 Lipman, Charles B., 1912, pp. 7, 8, 16, 17, 20.

7 I. J. Kligler.

8 Walcott, Charles D., 1915, p. 256.

In the section (Fig. 2, *A*) shown by the arrow, there is a little chain of cells closely similar to those in the existing species of *Azotobacter,* an organism that fixes atmospheric nitrogen and converts it into a form utilizable by the plant. It is related to the *Nitroso coccus, Nitroso monas* and *Nitrobacter,* and lives on simple salts with mannite ($C_6H_{14}O_6$)[9] as a source of carbon.

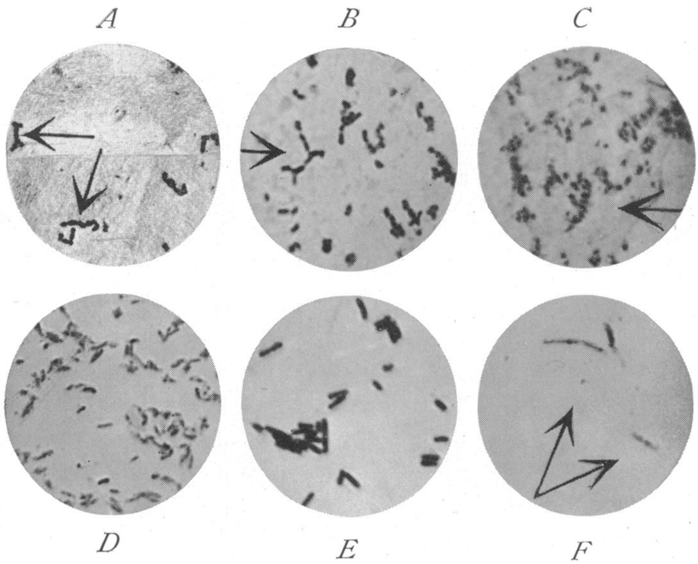

FIG. 2. *A*. Fossil bacteria from the Newland limestone (Algonkian) (after Walcott). *B*. Nitrifying bacteria found in soil. The arrow indicates a chain structure similar to that of Walcott's fossil bacteria. *C*. Nitrifying bacteria found in soils—a more complex type than the above. *D*. Nitrogen-fixing bacteria from the root nodules of legumes. Note the granular structure. *E*. Denitrifying bacteria found in soil and water. *F*. Bacteria stained to bring out the chromatin granules.

It was only after the chlorophyllic carbon-storing true plants had evolved that the second great group of nitrifying bacteria arose to develop the power of storing the *nitrogen of the atmosphere* through life association or symbiosis with plants, and of deriving their carbon, not from inorganic compounds, but from the carbohydrates of plants. Such users of atmospheric nitrogen and plant carbon include three general types: *B. radicicola,* associated with the root formation of legumes, *Clostridium* (anaerobic), and *Azotobacter* (aerobic).[10]

The gradual evolution of cell structure in these organisms can be partly traced despite their excessively minute size. The cell structure of the Algonkian and of the recent *Nitroso coccus* bacteria (Fig. 2, *A, B*) is very primitive and uniform in appearance, the protoplasm

[9] Mannite is needed by the higher forms of nitrifiers (*Azotobacter*), but not by the primitive types, and was probably not found until plant life flourished.

[10] Jordan, Edwin O., 1908, pp. 484–491.

being naked or unprotected: this primitive structure is also seen in *C*, another type of nitrogen fixer of the soil, which is chemically more complex because it can obtain its nitrogen either from the inorganic nitrogen compounds or from the organic nitrogen compounds (amino acids, proteins) which are fatal to the *Nitroso monas* and the *Nitrobacter* forms. The arrow points to a group of rods similar in appearance to those in *B*. A higher stage of granular structure appears in *D*, a nitrogen-fixer from the root nodules of legumes, which like *B* and *C* lives on inorganic chemical compounds but draws upon the atmosphere for nitrogen and upon sugar for its carbon: we observe an uneven granular structure in this cell. This may be an illustration of an early type of parasitic adaptation. The next type of bacterium (*E*) is a *denitrifier*, which derives its oxygen from the nitrates, reducing them to nitrites and free nitrogen and ammonia. A further stage of structural and chemical evolution is seen (*F*) in four elongated bacteria, each showing a rod-like but cellular form with a deeply staining chromatin or nuclear mass: the arrows point to cells showing these chromatin granules. This organism is chemically more complex in that it can secrete a powerful tryptic-like enzyme which enables it to utilize complex polypeptids and proteins (casein). Also it is an obligatory aerobic type, being unable to function in the absence of free oxygen.

It seems that the early course of evolution was in the line of developing a variety of complex molecules for performing a number of metabolic functions, and that the visible cell differentiation came later.[11] Step by step the chemical evolution and addition of increasingly complex actions, reactions, and interactions appears to correspond broadly with the structural evolution of the bacterial organism in its approach to the condition of a typical cell with its cell wall, protoplasm and chromatin nucleus. To sum up, the existing bacteria exhibit a series of primordial phases in the capture, storage and utilization of energy, and in the development of products useful to themselves and to other organisms and of by-products which cause interactions in other organisms. With the simplest bacteria which live directly on the lifeless world we find that most of the fundamental chemical energies of the living world are already established, namely,

(*a*) the protein and carbon storage, the primary food supply of the living world;

(*b*) the colloidal cell interior, with all the adaptations of colloidal suspensions, including

(*c*) the stimulating electric action and reaction of the metallic on the non-metallic elements; for example, the accelerations by iron, manganese, and other metals. Some bacteria carry positive, others negative ion charges;

[11] I. J. Kligler.

(*d*) the catalytic or enzyme action, both within and without the organism.

Thus the chemical composition of bacteria is analogous to that of the higher plant and animal cells, but no chlorophyll and no cellulose is found.

Bacterial suspensions manifest the characteristics of colloidal suspensions, namely, of fluids containing minute gelatinous particles which are kept in motion by molecular movement: these colloidal substances have the food value of protein and form the primary food supply of many Protozoa, the most elementary forms of animal life. Enzymes of three kinds exist, proteolytic, oxidizing and synthetic.[12] The proteolytic enzymes are similar to the tryptic enzymes of animals, being able to digest only the proteoses and amino acids but not the complex proteins. Powerful oxidizing enzymes are present but their character is not known. Synthetic enzymes must also exist though as yet there is no positive information concerning them. Like other forms of life, bacteria need oxygen for combustion in their intracellular actions and reactions; but free oxygen is not only unnecessary but actually toxic to the anaerobic bacteria, discovered by Pasteur in 1861, which derive their oxygen from inorganic and organic compounds. There is, however, a transitional group of bacteria, known as the *facultative anaerobes,* which can use either free, or combined oxygen, thus forming a link to all the higher forms of life in which free oxygen is an absolute essential. There is a group of the higher spore-forming bacteria which must have free oxygen. These constitute probably the last stage in bacterial evolution and form the link to the higher forms.

Armed with these physico-chemical powers, which may have been acquired one by one, the primordial bacteria mimic the evolution of the higher plant and animal world by an adaptive radiation into groups which respectively seek new sources of energy either directly from the inorganic world, or parasitically from the developing organic bacterial and plant foods in protein and carbohydrate form, the different groups living together in large communities and interacting chemically upon one another by the changes produced in the environment. For example, the iron bacteria discovered by Ehrenberg in 1838 obtain their energy from the oxidation of iron compounds, the insoluble oxide remaining stored in the cell and accumulating into iron as the bacteria die.[13] In general the beds of iron ore found in the pre-Cambrian strati-

[12] I. J. Kligler.

[13] It is claimed that iron bacteria play an important part in the formation of numerous small deposits of bog-iron ore and it seems possible that their activities may be responsible for extensive sedimentary deposits as well. Further, the fact of finding iron bacteria in underground mines opens the possibility that certain underground deposits of iron ore may have been formed by them. Harder, E. C., 1915, p. 311.

fied rocks, which have an estimated age of sixty million years, are believed to be of bacterial origin. Sulphur bacteria similarly obtain their energy from the oxidation of hydrogen sulphide.

Bacteria thus anticipate the plant world of algæ, diatoms and carbon-formers, as well as the animal world of protozoa and mollusca, by playing an important rôle in the formation of the new crust of the earth. This is observed in the primordial limestone depositions composed of calcium carbonate formed by bacterial action on the various soluble salts of calcium present in solution in sea-water, a process exemplified to-day[14] in the Great Bahama Banks where chalk mud is now precipitated through accumulation by *B. calcis.* Doubtless in the shallow continental seas of the primal earth such bacteria swarmed, as in the shallow coastal seas of to-day, having both the power of secreting and precipitating lime and, at the same time, of converting nitrogen combinations. In the warm oceanic waters the amount of lime deposited is larger and the *variety* of living forms is greater; but the *number* of living forms which depend for food on the algæ is less because the denitrifying bacteria which flourish in warm tropical waters deprive the algæ of the nitrates so necessary for their development. Again, where algal growth is scarce, the protozoic unicellular and multicellular life (plankton) of the sea, which lives upon the algæ, is also less abundant. This affords an excellent illustration of the great law of *the balance of the life environment through the equilibrium of supply of energy,* one aspect of the interaction of organisms with their life-environment. The denitrifying bacteria rob the waters of the energy needed for the lowest forms of plants, and these in turn are not available for the lowest forms of animal life. Thus in the colder waters of the oceans, where the denitrifying bacteria do not exist, the number of living forms is far greater, although their variety is far less.[15]

The so-called luminous bacteria also anticipate the plants and animals in light production,[16] which is believed to be connected with the oxidation of a phosphorescing substance in the presence of water and of free oxygen.

The parasitic life of bacteria began with their symbiotic relations with other bacteria, and was extended into intimate relations with the entire living world. The number of these organisms is inconceivable. In the daily excretion of a normal adult human being it is estimated that there are from 128 billion to 33 trillion bacteria, which would weigh approximately 5 5/10 grams when dried, and that the nitrogen in this dried mass would be about 0.6 gram, constituting nearly one half the total intestinal nitrogen.[17]

14 Drew, George H., 1914, p. 44.

15 Pirsson, Louis V., and Schuchert, Charles, 1915, p. 104.

16 Harvey, E. Newton, 1915, pp. 230, 238.

17 Kendall, A. I., 1915, p. 209.

Evolution of Protoplasm and Chromatin, the Two Structural Components of the Living World

It is still a matter of controversy[18] whether any bacteria, even at the present time, have reached the evolutionary stage of the typical cell with its cell wall, its contained protoplasm and its distinct nuclear form and inner substance known as chromatin. Some bacteriologists (Fischer) maintain that bacteria have neither nucleus nor chromatin; others admit the presence of chromatin but deny the existence of a formal nucleus; others contend that the entire bacterial cell has a chromatin content; while still others claim the presence of a distinctly differentiated nucleus containing chromatin. Most of them, however, are agreed as to the presence in bacteria of granules of a chromatin nature, while they leave as an open question the presence or absence of a structurally distinct nucleus. This conservative point of view is borne out by the fact that all the common bacteria have been found to contain *nuclein,* the specific nuclear protein complex; and is also sustained by the fact that the lowliest plants, the blue-green algæ (Cyanophyceæ), contain neither definitely formed nuclei nor chromatin bodies,[19] and are thus regarded as intermediate between bacteria and the higher green algæ (Chlorophyceæ).

It is also a matter of controversy among bacteriologists as to the very important question whether protoplasm or chromatin is the more ancient. Cell observers (Boveri, Wilson, Minchin), however, are thoroughly agreed on this point. Thus Minchin is unable to accept any theory of the evolution of the earliest forms of living beings which assumes the existence of forms of life composed entirely of protoplasm without chromatin.[20] All the results of modern investigations—the combined results, that is to say, of cytology and protistology—appear to him to indicate that the chromatin-elements represent the primary and original living units or individuals, and that the protoplasm represents a secondary product. As to whether chromatin or protoplasm is the more ancient, Boveri suggests that true cells arose through symbiosis between protoplasm and chromatin, and that the chromatin elements were primitively independent, living symbiotically with protoplasm. The more probable view is that of Wilson, that chromatin and protoplasm are coexistent in cells from the earliest known stages, in the bacteria and even probably in the ultra-microscopic forms.

The development of the cell theory after its enunciation in 1838 by Schleiden and Schwann followed first the differentiation of protoplasmic structure in the cellular tissues (histology). Since 1880 it has taken a new direction in investigating the *chemical and functional*

18 I. J. Kligler.

19 Loeb, Jacques, 1906, p. 106.

20 Minchin, E. A., 1916, p. 32.

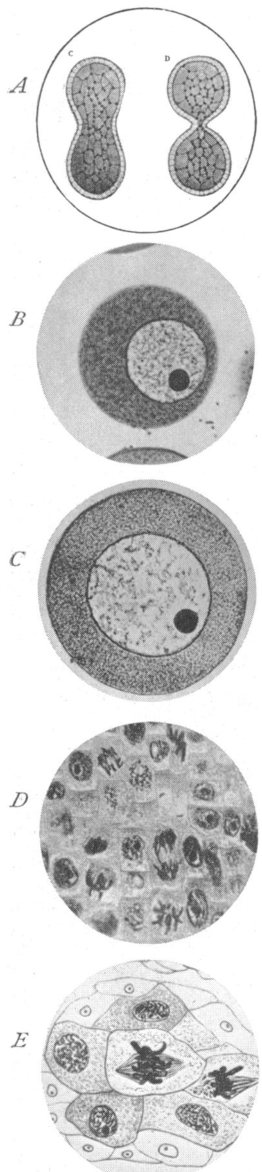

FIG. 3. CELL FORMS. *A. Achromatium*, a bacteria-like organism with diffused nucleus. *B.* Young ovarian egg of a sea-urchin. *C.* Ovarian egg of a sea-urchin. *D.* Root-tip of an onion. *E.* Embryo of *Sequoia sempervirens*. The mother-cells undergoing division. Two spindles of the reduction-division are shown.

separation of the chromatin. As protoplasm is now known to be the *expression,* so chromatin is now known to be the *seat* of heredity which Nägeli (1884) was the first to discuss as having a physico-chemical basis; the "idioplasm" postulated in his theory being realized in the actual structure of the chromatin as developed in the researches of Hertwig, Strasburger, Kölliker, and Weismann, who independently and almost simultaneously (1884, 1885) were led to the conclusion that the nucleus of the cell contains the physical basis of inheritance and that the chromatin is its essential constituent.[21] In the development from unicellular (Protozoa) into multicellular (Metazoa) organisms the chromatin is distributed through the nuclei to all the cells of the body, but Boveri has demonstrated that all the body cells lose a portion of their chromatin and only the germ cells retain the entire ancestral heritage.

Chemically, the most characteristic peculiarity of chromatin, as contrasted with protoplasm, is its phosphorus content.[22] It is also distinguished by a strong affinity for certain stains which cause its scattered or collected particles to appear intensely dark. Nuclein, which is probably identical with chromatin, is a complex albuminoid substance rich in phosphorus. The chemical, or molecular and atomic, constitution of chromatin infinitely exceeds in complexity that of any other form of matter or energy known. As intimated above (pp. 7, 8) it not improbably contains undetected chemical elements. Experiments made by Oskar, Gunther, and Paula Hertwig (1911–1914) resulted in the conclusion that in cells exposed to radium rays the seat of injury is chiefly, if not exclusively, in the chromatin:[23] these experi-

21 Wilson, E. B., 1906, p. 403.
22 Minchin, E. A., 1916, pp. 18, 19.
23 Richards, A., 1915, p. 291.

ments point also to the separate and distinct chemical constitution of the chromatin.

The principle formulated by Cuvier, that the distinctive property of life is the maintenance of the individual specific form throughout

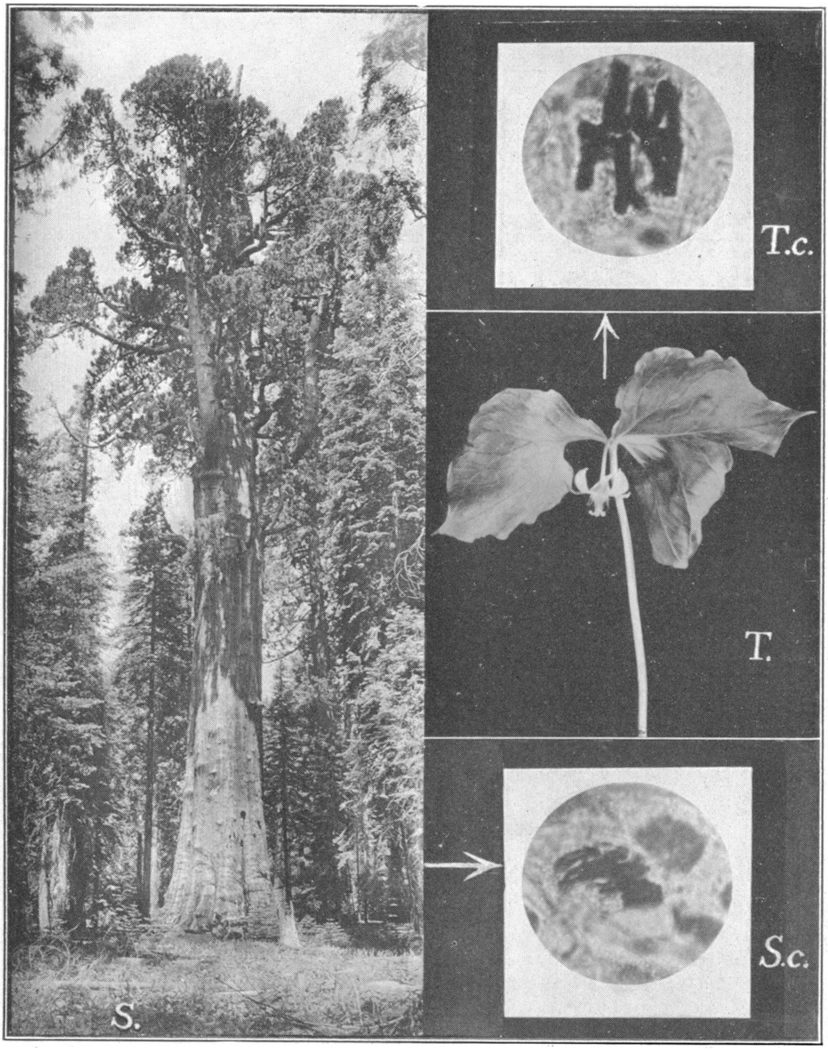

FIG. 4. *S. Sequoia Washingtcnia* or *gigantea*. *Sc.* Cell of *Sequoia sempervirens*, showing the chromosomes (chromatin bodies). *T. Trillium.* *Tc.* Cell of *Trillium sessile*, var. *gigcnteum*, showing the chromosomes in the same phase and with the same magnification as in the cell of Sequoia (*Sc.*).

the incessant changes of matter which occur in the inflow and outflow of energy, acquires wider scope in the law of the continuity of the germ plasm (*i. e.*, chromatin), announced by Weismann in 1883, for it is in

the chromatin that the ideal form is not only preserved, but through subdivision carried into the germ cells of all the present and succeeding generations. The continuity of life since it first appeared in Archeozoic time is the continuity of the physico-chemical energies of the chromatin; the development of the individual life is an unfolding of the energies taken within the body under the directing agency of the chromatin; and the evolution of life is essentially the evolution of the chromatin energies. It is in the inconceivable physico-chemical complexity of the chromatin that life presents its most violent contrast to any of the phenomena observed within the lifeless world.

Although each organism has its specific constant in the cubic content of its chromatin, the bulk of this content bears little relation to the size of the individual. This is illustrated by a comparison of the chromatin content of the cell nucleus of *Trillium,* a plant about sixteen inches high, with that of *Sequoia sempervirens,* the giant redwood tree of California, which reaches a height of from 200 to 300 feet and attains an age of several thousand years (Fig. 5). The chromatin content of such a nucleus is measured by the bulk of the chromosome rods of which it is composed. In the sea-urchin the size of the sperm nucleus, the most compact type of chromatin, has been estimated as about 1/100,000,000 of a cubic millimeter or 10 cubic microns in bulk.[24]

Within such a chromatin bulk there is yet ample space for an incalculable number of minute particles of matter. According to the figures given by Rutherford[25] in the first Hale Lecture the diameter of the sphere of action of an atom is about 1/100,000,000 of a centimeter, or 1/10,000,000 of a millimeter, or 1/10,000 of a micron—the unit of microscopic measurement. The electrons released from atoms of matter are only 1/1800 of the mass of the hydrogen atom, the lightest known to science, and thus the mass of an electron would be only 1/18,000,000 of a micron. These figures help us in some measure to conceive of the chromatin as a microcosm made up of an almost unlimited number of mutually acting, reacting and interacting particles; but

24 E. B. Wilson, letter of June 28, 1916.

25 It is necessary, observes Rutherford, to be cautious in speaking of the diameter of an atom, for it is not at all certain that the actual atomic structure is nearly so extensive as the region through which the atomic forces are appreciable. The hydrogen atom is the lightest known to science, and the average diameter of an atom is about 1/100,000,000 of a centimeter; but the negatively charged particles known as electrons are about 1/1800 of the mass of the hydrogen atom. . . . These particles travel with enormous velocities of from 10,000 to 100,000 miles a second. . . . The alpha particles produce from the neutral molecules a large number of negatively charged particles called ions. The ionization due to these alpha particles is measurable. . . . In the phosphorescence of an emanation of pure radium the atoms throw off the alpha particles with velocities of 10,000 miles a second, and each second five billion alpha particles are projected. Rutherford, Sir Ernest, 1915, pp. 113, 128.

while we know it to be the physical basis of inheritance and the presiding genius of all phases of development, we can not form the slightest conception of the mode in which the chromatin speck controls the destinies of *Sequoia gigantea* and lays down all the laws of its being for a period of five thousand years.

We are equally ignorant as to how the chromatin responds to the actions, reactions and interactions of the body cells, of the life environment, and of the physical environment, so as to call forth a new adaptive character,[26] unless it be through some catalytic agencies (p. 8). Yet in pursuing the history of the evolution of life upon the earth we may constantly keep before us our fundamental biologic law[27] that evolution lies within four complexes of energies, which are partly visible and partly invisible, namely:

1. The evolution of the physical environment;
2. The individual development of the organism, namely, of its protoplasm controlled and directed by its chromatin;
3. The heredity evolution of the chromatin with its constant addition of new powers and energies;
4. The evolution of the life environment, beginning with the protocellular chemical organisms and such intermediate organisms as bacteria, and followed by such cellular and multicellular organisms as the higher plants and animals.

Incessant competition, selection, intraselection (Roux), and elimination between all parts of organisms in their chromatin energies, in their protoplasmic energies, and in their actions, reactions and interactions with the living environment and with the physical environment.

Chlorophyll and the Energy of Sunlight

As bacteria seek their energy in the geosphere and hydrosphere, chlorophyll is the agent which connects life with the atmosphere, collecting the carbon from its union with oxygen in carbon dioxide. The utilization of the energy of sunlight in the capture of carbon from the atmosphere through the agency of chlorophyll marked the second great phase in the evolution of life, following the first bacterial phase. The chief energy elements, nitrogen and (less frequently) carbon, were captured by bacteria through molecule-splitting in the presence of heat, but without the powerful aid of sunlight.

It is the fossilized tissue of plants which leads us to the conclusion that the agency of chlorophyll is also extremely ancient. Near the base of the Archean rocks[28] graphites are observed in the Grenville series

[26] Wilson, E. B., 1906, p. 434.
[27] Osborn, H. F., 1912.
[28] Pirsson, Louis V., and Schuchert, Charles, 1915, p. 545.

and in the Adirondacks. The very oldest metamorphosed sedimentaries are mainly composed of shales containing carbon.

Since the carbohydrates constitute the basal energy supply of the entire plant and animal world,[29] we may examine the process even more closely than we have done above (p. 172). As a reservoir of life energy which is liberated by oxidation, hydrogen exceeds any other element in the heat it yields, namely, 34.5 calories per gram, while carbon yields 8.1 calories per gram.[30] The results of the most recent researches are presented by Wager.[31]

> The plant organ responds to the directive influence of light by a curvature which places it either in a direct line with the rays of light as in grass seedlings, or at right angles to the light as in ordinary foliage leaves. . . . Of the light that falls upon a green leaf a part is reflected from its surface, a part is transmitted, and another part is absorbed. That which is reflected and transmitted gives to the leaf its green color; that which is absorbed, consisting of certain red, blue, and violet rays, is the source of the energy by means of which the leaf is enabled to carry on its work.
>
> The extraordinary molecular complexity of chlorophyll has recently been made clear to us by the researches of Willstätter and his pupils; Usher and Priestley and others have shown us something of what takes place in chlorophyll when light acts upon it; and we are now beginning to realize more fully what a very complex photo-sensitive system the chlorophyll must be, and how much has yet to be accomplished before we can picture to our minds with any degree of certainty the changes that take place when light is absorbed by it. But the evidence afforded by the action of light upon other organic compounds, especially those which, like chlorophyll, are fluorescent, and the conclusion according to modern physics teaching that we may regard it as practically certain that the first stage in any photo-chemical reaction consists in the separation, either partial or complete, of negative electrons under the influence of light, leads us to conjecture that, when absorbed by chlorophyll, the energy of the light-waves becomes transformed into the energy of electrified particles and, that this initiates a whole train of chemical reactions resulting in the building up of the complex organic molecules which are the ultimate products of the plant's activity.

Chlorophyll absorbs most vigorously the rays between B and C of the solar spectrum,[32] which are the most energizing; the effect of the rays between D and E is minimal; while the rays beyond F again become effective. As compared with the primitive bacteria in which nitrogen figures so largely, chlorophyllic plant tissues consist chiefly of carbon, hydrogen, and oxygen, the chief substance being cellulose ($C_6H_{10}O_5$),[33] while in some cases small amounts of nitrogen are found, and also mineral substances, potassium, magnesium, phosphorus, sulphur, and manganese. On the contrary, it is the invariable presence of nitrogen

[29] Moore, F. J., 1915, p. 213.

[30] Henderson, Lawrence J., 1913, p. 245.

[31] Wager, Harold, 1915, p. 468.

[32] Loeb, Jacques, 1906, p. 115.

[33] Pirsson, Louis V. and Schuchert, Charles, 1915, p. 164.

which distinguishes the proteins of the bacteria: nitrogen is also a large constituent of animal proteins.

PERCENTAGE OF ELEMENTS IN THE PROTEINS[34]

Carbon	50.0 – 55.0
Hydrogen	6.9 – 7.3
Oxygen	19.0 – 24.0
Nitrogen	18.0 – 19.0
Sulphur	0.3 – 2.4

Closest to the bacteria in structure are the so-called "blue-green algæ" or Cyanophyceæ, found everywhere in fresh and salt water and even in hot springs, as well as on damp soil, rocks, and bark. The characteristic color of the Red Sea is due to a free-floating form of these blue-green algæ which in this case are red. Unlike the true algæ the cell nucleus of the Cyanophyceæ ordinarily is not sharply limited by a membrane, and there is no evidence of distinct chlorophyll-bodies, although chlorophyll is present. Their only method of reproduction is that known as vegetative multiplication, in which an ordinary working cell (individual) divides to form two new individuals. The sinter deposits of hot springs and geysers in Yellowstone Park are attributed to the presence of Cyanophyceæ.[35]

With the appearance of the true algæ the earth-forming powers of life become still more manifest and few geologic discoveries of recent times are more important than those growing out of the recognition of algæ as earth-forming agents. As early as 1831 Lyell remarked their rock-forming powers. It is now known that among the various lower organisms concerned in earth-building, the algæ rank first, the foraminifera second, and the corals third. In a forthcoming work by F. W. Clarke and W. C. Wheeler they remark upon these earth-building activities as follows:

> The calcareous algæ are so important as reef builders, that, although they are not marine invertebrates in the ordinary acceptance of the term, it seemed eminently proper to include them in this investigation. In many cases they far outrank the corals in importance, and of late years much attention has been paid to them. On the atoll of Funafuti, for example, the algæ *Lithothamnium* and *Halimeda* rank first and second in importance, followed by the foraminifera, third, and the corals, fourth.

Algæ are probably responsible for the formation of the very ancient limestones; those of the Grenville series at the very base of the pre-Cambrian are believed to be over 60,000,000 years of age. The algal flora of the relatively recent Algonkian time,[36] together with calcareous

[34] Moore, F. J., 1915, p. 199. Nucleic proteins contain a notable amount of phosphorus as well.

[35] Coulter, John Merle, 1910, pp. 10–14.

[36] Walcott, Charles D., 1914.

bacteria, developed the massive limestones of the Tetons. Clarke observes:

> We are now beginning to see where the magnesia of the limestones comes from and the algæ are probably the most important contributors of that constituent.

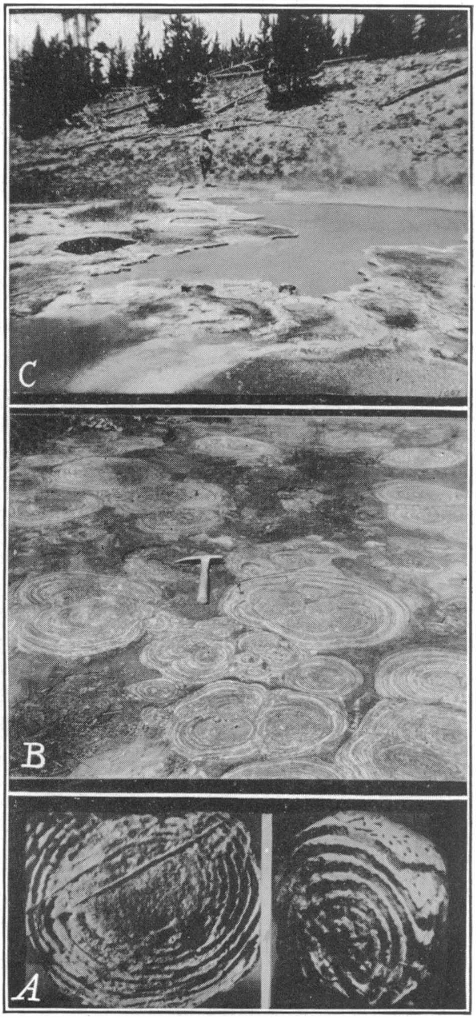

FIG. 5. *A*. Fossil algæ (*Newlandia concentrica, Newlandia frondosa*) from the Algonkian Belt Series of Montana. Walcott. *B*. Fossil calcareous algæ (*Cryptozoon proliferum*) from the Cambrian limestone of Lester Park near Saratoga Springs, New York. *C*. An algal pool near the Great Fountain Geyser, Yellowstone Park. Walcott. Photographed by H. P. Cushing.

Thus representatives of the Rhodophyceæ contribute as high as 87 per cent. of calcium carbonate and 25 per cent. of magnesium carbonate.

Species of *Halimeda,* however, calcified algæ belonging to the very different class Chlorophyceæ, are important agents in reef-building and land-forming, yet are almost non-magnesian.[37]

The Grenville series at the base of the Paleozoic is essentially calcareous, with a thickness of over 94,000 feet, nearly eighteen miles, more than half of which is calcareous.[38] Thus it appears probable that the surface of the primordial continental seas swarmed with these minute algæ, which served as the chief food magazine for the floating protozoa; but it is very important to note that their life is absolutely dependent

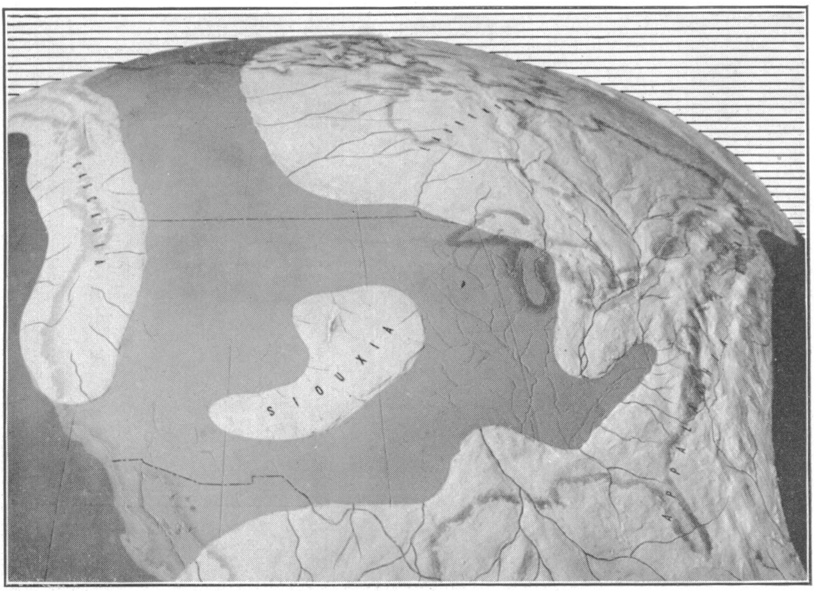

FIG. 6. NORTH AMERICA IN PRE-CAMBRIAN (CROIXIAN) TIME. Detail from globe model by Chester A. Reeds and George Robertson, after Schuchert.

upon phosphorus and other earth-borne constituents of sea-water, as well as upon nitrogen, also earth-borne, and due to bacterial action; for where the denitrifying bacteria rob the sea-water of its nitrogen content the algæ are much less numerous.[39] Silica is also an earth-borne, though mineral, constituent of sea-water which forms the principal skeletal constituent of the shells of diatoms, minute floating plants especially characteristic of the cooler seas which form the siliceous ooze of the sea-bottoms.

(*To be continued*)

[37] M. A. Howe, letter of February 24, 1916.

[38] Pirsson, Louis V., and Schuchert, Charles, 1915, pp. 545, 546.

[39] *Op. cit.,* p. 104.

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